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Computer-Based Detection and Analysis of Heart Sound and Murmur

M. El-Segaier,[1] O. Lilja,[2] S. Lukkarinen,[3] L. Sörnmo,[2] R. Sepponen,[3] and E. Pesonen[1]

[1]Department of Paediatrics, Division of Paediatric Cardiology, Lund University Hospital, Sweden; [2]Department of Electroscience, Lund University, Sweden; and [3]Department of Applied Electronics, Helsinki University of Technology, Helsinki, Finland

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Abstract—To develop a digital algorithm that detects first and second heart sounds, defines the systole and diastole, and characterises the systolic murmur. Heart sounds were recorded in 300 children with a cardiac murmur, using an electronic stethoscope. A Digital algorithm was developed for detection of first and second heart sounds. R-waves and T-waves in the electrocardiography were used as references for detection. The sound signal analysis was carried out using the short-time Fourier transform. The first heart sound detection rate, with reference to the R-wave, was 100% within 0.05–0.2R-R interval. The second heart sound detection rate between the end of the T-wave and the 0.6R-R interval was 97%. The systolic and diastolic phases of the cardiac cycle could be identified. Because of the overlap between heart sounds and murmur a systolic segment between the first and second heart sounds (20–70%) was selected for murmur analysis. The maximum intensity of the systolic murmur, its average frequency, and the mean spectral power were quantified. The frequency at the point with the highest sound intensity in the spectrum and its time from the first heart sound, the highest frequency, and frequency range were also determined. This method will serve as the foundation for computer-based detection of heart sounds and the characterisation of cardiac murmurs.

Keywords—Detection algorithm, Signal analysis, Short-time Fourier transform, Systolic murmur.

INTRODUCTION

Despite remarkable advances in imaging technologies for the heart, the clinical evaluation of cardiac defects by auscultation has remained a main diagnostic method for congenital heart diseases. In experienced hands the method is effective, reliable, and cheap. However, tools for objective analysis and adequate documentation of the findings are still lacking.

The acoustic performance of commercial stethoscopes is far from high fidelity.[1,7] Furthermore, the performance of the ear has several physical limitations. The acoustic signals from the heart contain information which cannot be analyzed by the human ear.[14] The sensitivity of the ear in regard to frequency follows a logarithmic scale. The ear hears changes in frequency better than changes in intensity. Sounds with higher frequencies are perceived as being louder than those with lower frequencies of same intensity. Changes in frequency may be interpreted as changes in intensity. In the presence of high-frequency sounds, the ear may be unable to detect low-frequency ones which follow immediately.[9]

Recent advances in data recording technology and digital signal processing have made it possible to record and analyze the sound signals from the heart.[2,4,5,11,12] However, for computer analysis of the acoustic signals from the heart, it is essential that different components of heart cycle can be timed and separated.[6] We have developed a computerized method for detecting heart sounds, first (S_1) and second (S_2), and defining the systole and diastole in auscultation signals. The analysis of the systolic and diastolic murmurs can be based on the frequency of the signal, its intensity and location of the highest intensity point in the signal spectrum.

METHODS

Patients

Patients with cardiac murmur who visited the outpatients paediatric cardiology clinic at Lund University Hospital between September 1998 and December 2001 were considered as potential candidates for heart sound recording. Out of approximately 13,500 patients, 300 children with ages ranging between 1 month and 17 years (median 5.5 years), were arbitrarily examined with the digital heart sound recorder.[8] The study was approved by the ethics committee of Lund University Hospital, and all children and/or their parents gave informed consent to participate in the study. All patients were examined with echocardiography

Address correspondence to Milad El-Segaier, Department of Paediatrics, Division of Paediatric Cardiology, Children's Hospital, Lund University Hospital, SE-221 85 Lund, Sweden. Electronic mail: milad.el-segaier@skane.se

Abbreviations: S_1 first heart sound; S_2 second heart sound; ECG electrocardiography; STFT Short-time Fourier transform; R-R interval between R waves in ECG signal; R-T interval between R and T waves in ECG signal.

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by an experienced cardiologist (M. E. S.). The recorded sound files were inspected to assess their quality. Twenty-four sound files were excluded from further analysis because of artefacts or low-amplitude signals.

The remaining recorded files, from 276 patients, were further studied regarding heart sound detection and determination of systole and diastole.

Data Acquisition

The cardiac sound signals were recorded for 40–45 s with a PC-based phonocardiographic device developed at the Helsinki University of Technology.[8] The recording transducer consisted of an electric microphone (Welleman MCE-2000, frequency range 20–20,000 Hz, self-noise level less than 34 dB, signal-to-noise ratio greater than 58 dB, sensitivity -44 ± 4 dB) within a cylindrically shaped cup made of PVC (poly vinyl chloride) with an outer diameter of 20 mm, inner diameter of 10 mm, inner depth of 7 mm, and a flat frequency response from 1 Hz to 2 kHz. The transducer was fixed firmly on the chest wall using a skin-friendly double-sided adhesive tape. Cardiac sounds were recorded at left parasternal intercostal spaces 2, 3, and 4, and at the apex, in the supine position. To encourage cooperation, young toddlers (10 months to 3 years of age) were examined in their parent's arms, sometimes combined with diversion of their attention with a silent moving toy. No sedation was used. The examination room did not have special sound insulation. The signal was amplified by 40 dB in order to compensate for signal intensity attenuation due to the acoustic properties of the chest wall, such as subcutaneous fat. The amplified signal was digitized with 16 bits resolution and 11.025 kHz sampling frequency using a National Instruments PU-MIO-16XE 10 Data-acquisition card. Customized software was written for recording and monitoring of the sound signals. The electrocardiogram (ECG) was recorded simultaneously with sound signals.

Automatic Spectral Analysis

Software was developed for automatic detection and analysis of heart sounds and murmurs. The ECG signals, high-pass filtered in order to remove baseline wander, were used as a reference for heart sound detection. The R-waves in the ECG signal were detected using an envelope-based detection algorithm.[10] The time intervals between R-wave peaks (R-R) and between R-waves and the peaks of T-waves (R-T) were measured. The R-R and R-T intervals were used as a reference for heart sound detection. R-R intervals with a length variation greater than $\pm 60\%$ from the preceding interval were excluded. Sound signals, band-pass filtered with cut-off frequencies of 40 and 1100 Hz, were processed using the Short-Time Fourier Transform (STFT). Even if the first (S_1) and second (S_2) heart sounds are usually splitted, the detection of separate components is not essential for the definition of systole and diastole. The sound signal with highest intensity is detected within a predefined interval and considered as S_1 and S_2 correspondingly. The detection of S_1 and S_2 was based on the time function describing the total spectral power in the interval 40–100 Hz.[14,15] The signal with the largest spectral power, within the interval 0.05R-R to 0.2R-R, was selected as S_1, provided that the selected signal corresponded to a well-defined peak in the time function. The peak was considered as well defined if the intensities of the surrounding signals, within an interval of 0.05R-R, were less than 10% of the intensity of the peak. The detection of S_2 was performed by the same approach while R-waves and the peak of T-waves were used as references, within the interval from 1.2R-T to 0.6R-R.

With increase in heart rate, the length of systole has a decreasing trend whereas diastole decreases significantly. Therefore S_2 is located relatively later within the heart cycle at higher heart rates. (Fig. 1). Because of age-related changes in heart rate and variation in S_2 location in relation to the R-R interval lengths, the algorithm for S_2 detection was adjusted and tested in regards to different location of S_2, as will be presented and explained in the Results and Discussion section.

Systolic Murmur Analysis

For the analysis of systolic murmur, 20% from the beginning and the last 30% of systole were rejected in order to avoid overlap between heart sounds and systolic murmurs. The systolic segments were analyzed with regards to the maximum intensity, its average frequency (the means of the frequencies measured per unit time), mean spectral power in dB (mean value of sound intensities in the spectrum), the time from S_1 and the frequency of the signal at the point with the maximal sound intensity, the highest frequency that generate an intensity of 0.1 dB, and frequency range between the highest frequency and 40 Hz (the frequency of the high-pass filter). The location of the highest intensity on the chest wall, punctum maximum, was determined for each patient.

To minimize the influence of high-frequency artefacts (crying, motion artefacts, breathing, and room noise), the mean intensity in the spectrum above and below 300 Hz was measured. The cardiac cycle was excluded if the mean intensity in the upper frequency region was higher than in the lower frequency region.

RESULTS AND DISCUSSION

Heart Sound Detection

The recording was easily and successfully performed in a normal outpatient clinic, and took less than 10 min, even in young children. Detection of the heart sounds (S_1 and S_2), based on STFT analysis was possible at high detection rates, 100% for S_1 and 97% for S_2.

Linear prediction analysis has been reported to be effective in heart sound detection even in cases of S_2 buried in cardiac murmur.[6] In this analysis heart sounds detection was based on finding local maximum peaks. Using only R-waves in the ECG signal as reference, an earlier algorithm has been developed to detect heart sounds.[3] In that algorithm difficulties in S_2 detection caused by changes in S_2 location in relation to the R-R interval, due to heart rate variation, were not highlighted. In the paediatric population heart rates are affected by age or incipient heart failure. Criteria for detection of S_2 at different heart rate have to be developed. In the following section we will present the stages in the development of the algorithm for S_2 detection in the presence of varying heart rate with or without long and intense systolic murmur.

Initially, detection of S_2 was programmed to take place at 0.45R-R $\pm$ 0.1R-R, i.e. between 0.35 and 0.55R-R [Fig. 2(a)]. This gave a high detection rate in healthy children with physiological murmur and normal heart rate. However, high heart rate, which is especially associated with congenital heart diseases, decreased the detection rate. A good detection rate of S_2 in presence of high heart rate was obtained in records when the algorithm was programmed to detect S_2 within the interval 0.6R-R $\pm$ 0.1R-R, i.e. between 0.5 and 0.7R-R [Fig. 2(b)]. However, in children with physiological murmur and normal heart rate, S_2 was located even earlier. Therefore, the detection period was changed to start from 0.35R-R [Fig. 2(c)]. This algorithm allowed a high detection rate in children with physiological murmur or with high heart rate, but remained not to function well in presence of long and intense pathological systolic murmurs such as those associated with ventricular septal defect, mitral insufficiency, severe aortic stenosis, or open ductus arteriosus. In such cases, the S_2 peak is not prominent in relation to the systolic murmur signal.

A combination of R-R and R-T intervals was necessary to solve this problem. S_2 never occurs before the end of T-waves, and the end of the T-wave is located at approximately 1.2R-T (1.2 times the interval between the peak of R-wave and the peak of T-wave). The detection interval was defined as being between the end of the T-wave (1.2R-T) and 0.6R-R [Fig. 2(d)]. By using this combination of R-R and R-T intervals, the S_2 detection rate was correct in 97% of records, even with variation in heart rate or the presence of long and intense murmurs.

S_1 was correctly detected within the interval 0.05–0.2R-R in all recordings, and was found not to be affected by changes in heart rate.

S_2 consists of two components, aortic (A_2) and pulmonary (P_2) components. The interval between these two components and its changes with respiration has important clinical significance. Small or absent respiratory variation of S_2 is the hallmark of auscultation finding in patients with ASD.[13,16] The principle for detection in the presented algorithm was based on defining, within limited and defined interval and frequency range, sound signal with largest spectral power and considers it as S_2. Normally A_2 has higher intensity than P_2 but both components are included in S_2. The purpose of the presented algorithm is to find heart sounds and define the systole for systolic murmur analysis. Splitting of S_2 and its frequency content does not affect the detection process.

Systolic Murmur Analysis

Some cardiac cycles had to be eliminated due to artefacts, as described in the Methods section. Signals from heart sounds, S_1 and S_2, may partially overlap the systolic murmur, making identification of the beginning of systolic murmur uncertain. Therefore, a systolic segment from 20 to

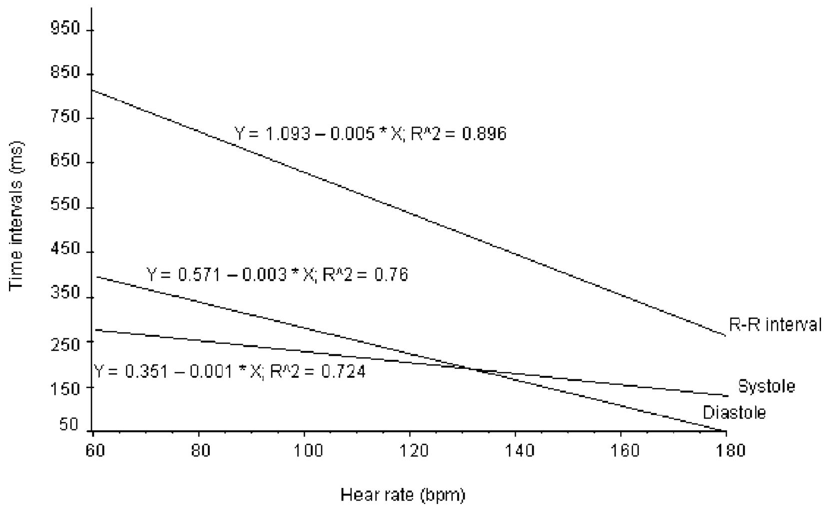

FIGURE 1. Correlation between heart rate and the length of systole, diastole, and R-R interval. The length of systole has a decreasing trend but is quite stable whereas diastole decreases significantly. Therefore S_2 locate, in higher heart rates, relatively later within heart cycle. ms = millisecond; bpm = beat per minute.

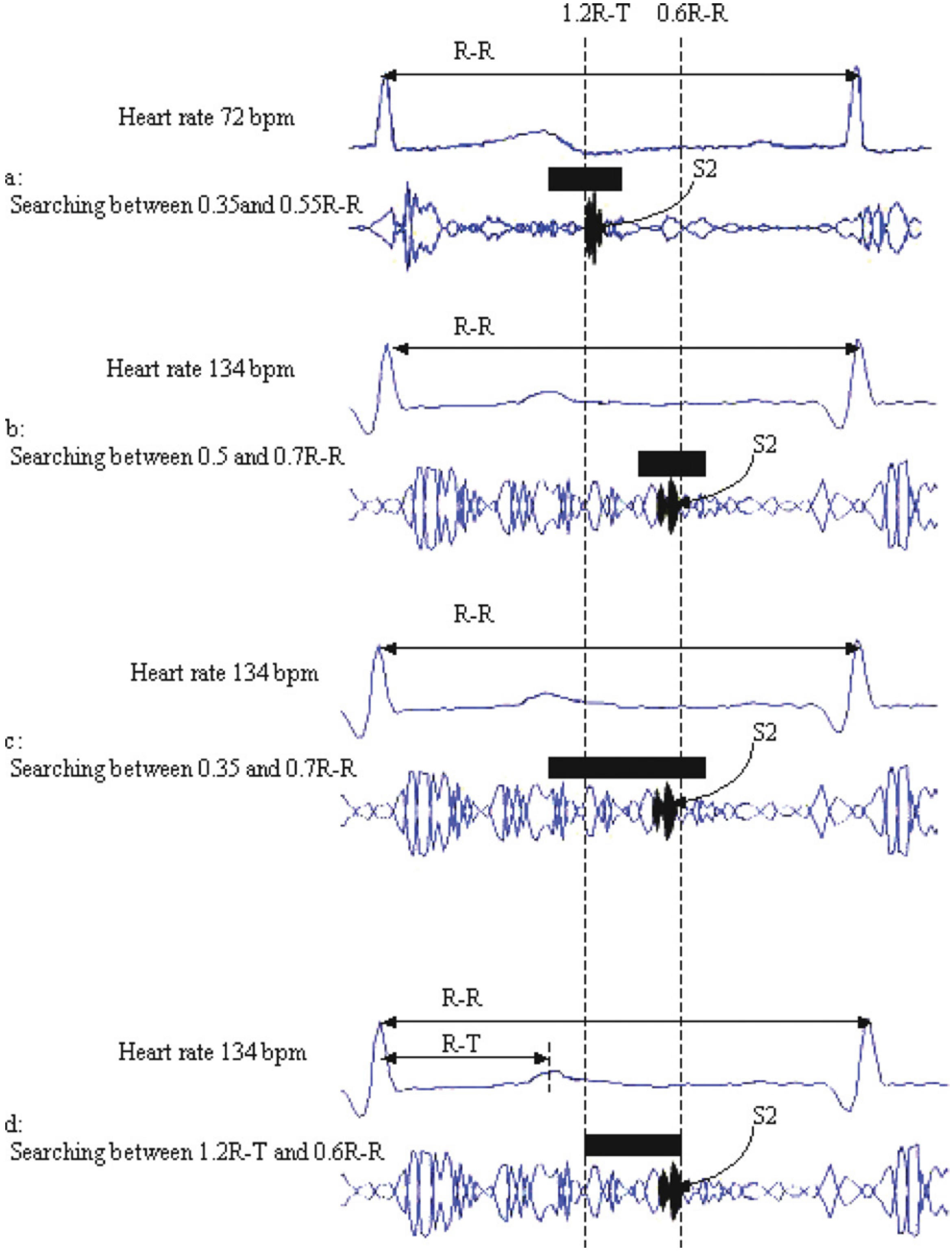

FIGURE 2. The detection algorithms for S_2. Dark rectangles indicate the searching intervals. The two dotted vertical lines indicate the final detection interval. (a) Detection of S_2 in association with normal heart rate. Searching between 0.35R-R and 0.55R-R. At higher heart rate (as seen in b, c and d) S_2 falls after this interval. (b) Detection of S_2 in association with high heart rate and intense systolic murmur. Searching between 0.5R-R and 0.7R-R. Searching interval is not covering S_2 at normal heart rate as seen in (a). (c) Searching between 0.35R-R and 0.7R-R. Searching interval covers S_2 both at normal and high heart rate but this increases risk of false detection (see text) if long and intense murmur is present. (d) Searching between 1.2R-T and 0.6R-R. Searching interval covers S_2 both at normal and high heart rate. The detection rate is 97% even if long and intense murmur is present. R-R = interval between R-waves in ECG; R-T = interval between R and T waves in ECG; bpm = beat per minute; S_2 = second heart sound.

70% between S_1 and S_2 was selected for the final analysis. The selected systolic segment was far enough from S_2 to avoid its early waves. Late waves of S_1 had to be removed by the high-pass filter at 40 Hz. The average frequency in the systolic segment could be verified by calculating the mean value of the frequencies measured per unit time. The maximum intensity and the mean spectral power were measured in dB. The point with the highest sound intensity, its frequency and location in the spectrum, the highest frequency, and the frequency range were determined to characterize the murmur. The location of the maximum intensity on the chest wall, punctum maximum, was determined for each patient. This was chosen from among the four registration points: left parasternal intercostal spaces 2, 3, and 4, and the apex. All measured data can be saved in an Excel file for further analysis. These variables can be used, in combination with the clinical assessment, in computer-based diagnosis and evaluation of noncyanotic congenital heart disease.

The evaluation of cardiac murmur by auscultation using the ordinary acoustic stethoscope is a highly sensitive and specific method.[17] However, one of the main limitations of auscultation is the lack of adequate documentation of the finding. The comparison of the auscultation findings with the earlier ones during follow-up assessments is important information about changing hemodynamics in children with congenital cardiac defects. By using a stethoscope this judgment will depend on the memory of the clinician; comparison of the findings between clinicians is unreliable. Our method shows both the spectrum and "the morphology" of the auscultation signals.

Novelty of the Algorithm

The novelty of the presented algorithm is its ability to detect correctly the heart sounds, particularly S_2, in the presence of variable heart rate and in association with long and intense systolic murmur. The detection rate is high. The broad age spectrum during childhood gives large variation in heart rate, i.e. heart rate is age-dependent. Congenital cardiac defect may induce variation in heart rate especially when they cause heart failure. Heart rate variation and long and intense systolic murmur increase the risk for false detection of heart sounds and, consequently, false definition of systole and diastole. The presented algorithm gives solution to this problem and can be used as a first step toward computer-based detection of heart sounds and analyses of auscultation findings in children.

Limitations of the Algorithm

In this study the diagnoses of congenital cardiac defects were known; therefore the utility of the algorithm in records from patients with unknown diagnosis is currently untested. A blind study to assess the algorithm utility is needed. By excluding the early part of systole, some pathological conditions, e.g. small muscular ventricular septal defects with diagnostic findings early in systole, can be missed. Moreover, early systolic clicks which are important auscultation findings, e.g. in valvular pulmonic and aortic stenosis, as well as in association of bicuspid aortic valve, will be ruled out from the analysis.

The ability of the algorithm to separate different types of cardiac murmurs, physiological versus pathological, was not a scope of this article.

CONCLUSIONS

Signal analysis for the detection of heart sounds (S_1 and S_2) and murmur analysis is possible with high success rate. This is the first step toward the computer-based analysis of auscultation findings.

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